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Estimating Optimum Irrigation Discharge under Furrow Irrigation in Afghanistan

By

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Summary：Management and control of surface irrigation, specifically furrow irrigation, is widely used despite its often low irrigation efficiency, which can be attributed mainly to the complexity of the interactions between field design, soil infiltration characteristics, and irrigation management practices. The objective of this study is to introduce a method for estimating optimum irrigation discharge that can reduce deep percolation for furrow irrigation. In this study, a mathematical model of surface irrigation using water advance testing was used to determine the optimum irrigation discharge in the cultivation of tomatoes and to compare the irrigation application efficiency with existing furrow irrigation. Finally, this water advance method may help to reduce the amount of irrigation water required for tomato crop cultivation in Kabul, Afghanistan.

Key words：furrow irrigation, water balance equation, water advance, optimum irrigation discharge, Afghanistan

Introduction

Afghanistan is a landlocked country approximately located in the center of Asia. It is bordered by Pakistan on the south and east; Iran on the west; Turkmenistan, Uzbekistan, and Tajikistan on the north; and China on the far northeast. Agriculture employs 80% of the Afghan population and accounts for more than half of its gross domestic product (GREGORY *et al*., 2010). The arable agricultural resource base of Afghanistan is about 8 million ha, which is 12% of the total land area. There are roughly 3.9 million ha of cultivated land, of which 1.3 million ha is rain fed, and 2.6 million ha is irrigated (ASAD, 2002). The major cereal crops in Afghanistan include: wheat, barley, rice and maize at the same time, the major vegetable crops include: melon, watermelon, onion, tomato and potato, meanwhile, the major fruit crops and vines include: grapes, almond, apricots, pomegranate and apples (ICARDA, 2003). This irrigated area produces almost 85% of all agricultural products. In Afghanistan, surface irrigation methods such as furrow, border, and basin irrigation are used. However, application efficiencies and distribution uniformities are very low due to high runoff and deep percolation losses (LATIF and ITTFAQ, 1998). Therefore, minimizing deep percolation and runoff while meeting the irrigation requirements of crops can increase irrigation performance.

On the other hand, surface irrigation, especially furrow irrigation, is one of the oldest methods of irrigation and remains a common technique used with furrow crops across the world (KOECH *et al*., 2014). Unfortunately, these methods often have lower efficiencies; for these reasons, several management techniques have been developed to reduce water losses during irrigation. In this case, no prior research has been done in Afghanistan, and only a few studies estimating the infiltration parameters for furrow irrigation have been conducted in other countries (VALIANZAS, *et al*., 2001; LANGAT *et al*., 2008; HOLZAPFEL *et al*., 2004; ABDELMONEM, 2011).

The objective of this study is to introduce a method for estimating the optimum irrigation discharge that can reduce deep percolation for furrow irritation. In this study, a mathematical model of surface irrigation was used to determine the optimum irrigation discharge in the culti-

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vation of tomatoes and to compare irrigation application efficiency with that of existing furrow irrigation.

Materials and Methods

(1) Infiltration model

Infiltration is one of the most important soil parameters in the design and evaluation of surface irrigation methods (ZIEMBELMAN, 1987). Estimation of soil infiltration is a major problem of irrigation studies due to the importance of properly selecting the technique used to determine the parameters of the infiltration models; the use of empirical infiltration models; and their dependence on soil moisture, soil characteristics, and surface roughness (HOLZAPFEL *et al.*, 1988; WALKER and BUSMAN, 1990). A number of infiltration equations attempt to explain the process of infiltration (CHRISTIANSEN, *et al.*,1966; WATANABE *et al.*,1996; ESFANDIARI and MAHESHWARI, 1997; ALVAREZ, 2003). In this study, the volume balance equation during an irrigation event is used as shown in *Eq.* (1). The left side of *Eq.* (1) is the volume of water applied to a furrow. The right side of the equation shows the sum of the infiltrated volume and the volume accumulated on the soil surface along a furrow.

$$qt=\int_0^x \Phi(t-\tau)\,d\zeta+\mu x, \qquad \cdots\cdots \; Eq.\ (1)$$

where q is the water supply amount per unit time (discharge), Φ (T) $=\alpha_0 T^{\beta}{}_0$ is the cumulative infiltration amount in T time, $\alpha_0=\alpha/(1+\beta)$,

$\beta_0=1+\beta$, α and β are intake coefficients, x is the water advance distance, t is the time the water was applied, τ is arrival time when the water reached ζ (advance distance), and μ is the average cross-sectional area of the surface flow.

The analytical solution of the above integral equation (Shirai, 1968) can be expressed as;

$$\upsilon=x/t,\ \upsilon_o=q/\mu,\ \zeta=\zeta_o t^{1+\beta} \qquad \cdots\cdots \; Eq.\ (2)$$

$$\zeta_o=\alpha\Gamma(1+\beta)/\mu,\ \upsilon/\upsilon_0=F \qquad \cdots\cdots \; Eq.\ (3)$$

When ζ is small ($\zeta<1$),

$$F=1-\frac{\zeta}{\Gamma(3+\beta)}+\frac{\zeta^2}{\Gamma(4+2\beta)}-\cdot\cdot=\sum\frac{(-1)^n\zeta^n}{\Gamma(n+2+n\beta)}, \qquad \cdots\cdots \; Eq.\ (4)$$

When ζ is large ($\zeta>1$)

$$F=\frac{1}{\Gamma(1-\beta)}\ \frac{1}{\zeta}-\frac{1}{\Gamma(-2\beta)}\ \frac{1}{\zeta^2}+\frac{1}{\Gamma(-1-3\beta)}\ \frac{1}{\zeta^3}\cdots +\frac{(-1)^n}{\Gamma(1-n-n\beta-\beta)}\ \frac{1}{\zeta^{n+1}}+\cdot\cdot, \qquad \cdots\cdots \; Eq.\ (5)$$

where υ is the velocity of the water advance (m/s), x is the distance of the advance (m), t(s) is required for the water advance to reach a distance of x in furrow, and υ_0 is the initial velocity of water advance in the inlet furrow.

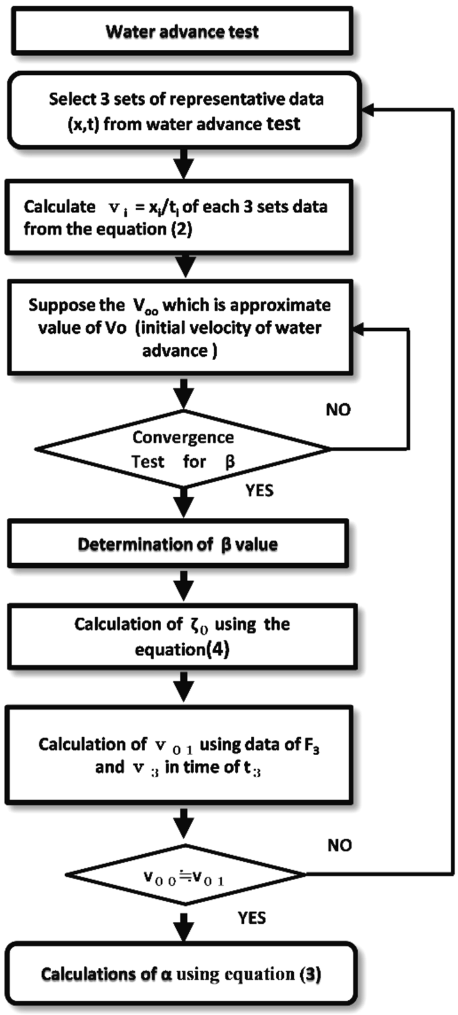

Fig. 1 Flow chart for calculating intake coefficients of α and β

This mathematical model was used in this study to conduct numerical experiments for determining the optimum irrigation discharge. We applied this equation to determine the intake coefficients and estimate the distribution of infiltration using furrow irrigation. This calculation procedure is shown in Fig. 1.

Finally, an optimum irrigation discharge for tomato crops was found based on the application efficiency of furrow irrigation with different discharges.

(2) Field measurement

Water advance tests were conducted at the Badam Bagh Agricultural Research station in Kabul, Afghanistan. The area is semi-arid with an average annual rainfall of 350 mm, average relative humidity of 31% in summer and of 52% in winter, and average air temperatures vary from minus 2℃ in winter to 22℃ in summer. According to the textural triangle classification of the International Society of Soil Science, the soil type is clay loam. The soil pH is 8. As shown in Fig. 2, furrows were 40 m long with 0.2 m bed width, 0.7 m surface width, and a depth of 0.3 m. The average slope of furrows was approximately flat with 0.02 % along the direction of irrigation.

In this upland field, tomatoes were cultivated using furrow irrigation. Irrigation water was taken from a deep well at this station. When the water advance reached the end of furrow, the irrigation water was immediately stopped. The irrigation discharge for the tomato crop was 0.00148 m^3/sec, similar to the typical amount of discharge in a farmer's irrigated agricultural field. The reaching time of the water's advance was measured at each 5-m distance along the furrow in order to calculate the intake coefficients (α, β) and the cumulative infiltration amount. To measure the soil moisture contents, soil samples were taken at depths of 0.05 m every 5 m before and after conducting the water advance test.

Results and Discussion

(1) Water advance tests and intake coefficients

The result of the water advance tests using actual farmer's irrigation water discharge is shown in Table 1. The intake coefficients of α and β were 4×10^{-4}, -0.4988, respectively. The average sectional area of the surface stream (μ) was 9.6786×10^{-3}.

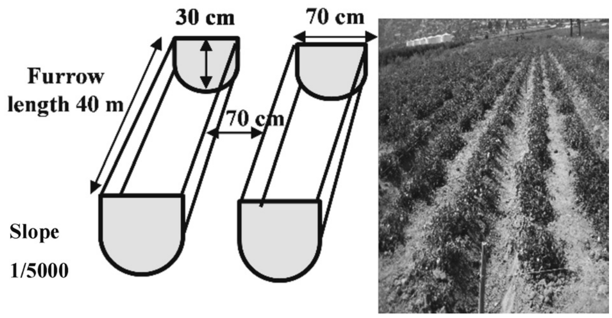

Fig. 2 Cross section of furrows and photo of the experimental field

Table 1 Result of water advance test and calculation of cumulative infiltration amounts, $q = 0.00148\ m^3/s$

advance distance (m)	water advance time (s)	infiltration time (s)	cumulative infiltration amount (m^2)
0	0	627	0.0201626
5	40	587	0.0195072
10	100	527	0.0184808
15	174	453	0.0171309
20	274	353	0.0151175
25	378	249	0.0126911
30	486	141	0.0095432
25	580	47	0.0055021
40	627	0	0

(2) Cumulative infiltration water amount

Cumulative amounts of water infiltration were calculated at each 5-m distance (Table 1). Distribution of infiltration amounts is described in Fig. 3.

When the water advance reached the end of the furrow, irrigation was immediately stopped. At this time, the total amount of irrigated water (qt) was 9.338×10^{-1} (m^3). The amount of water infiltrated into the soil layer (S1) was calculated using Simpson Rule (Barrass and Derrett, 2010). The infiltrated amount of water was 5.430×10^{-1} (m^3), and the amount of remaining surface water in 40-meters length of furrow (μx) was 3.991×10^{-1} (m^3). After the remaining surface water amount (S2) was infiltrated into the soil layer and calculated by changing the value of Δt as described in Fig. 3, the total amount of irrigated discharge (qt) was 9.338×10^{-1} (m^3). The amount of infiltrated water (S1 + S2) was 9.335×10^{-1} (m^3). The relationship between the total water supply (qt) and the total infiltration amount (S1 + S2) is as follows:

$$qt = 9.338\times10^{-1}\ (m^3) \fallingdotseq S1 + S2 = 9.335\times10^{-1}\ (m^3)$$

This shows that the two values are approximately equal.

(3) Application efficiency of irrigation water

As for the application efficiency of irrigation water, the amount of water stored in an effective soil layer is divided by the total amount of irrigation water. The application efficiency value of furrow irrigation managed by a local farmer was 57.4 %, as shown in Fig. 3. In order to determine the maximum value of irrigation application efficiency, we calculated the distribution of the infiltration amount with different irrigation discharges, such as 0.0011, 0.002, and 0.003 m^3/sec, in order to compare the application efficiency to that of conventional irrigation discharge (0.00148 m^3/sec). The water requirement for tomato crops was 4.26 mm/day in August 2014 using FAO CROPWAT program 8.0. The tomato-growing period was mid-season. The irrigation interval was 7 days, which is the same interval farmers use to irrigate their vegetable crop. The crop water requirement for a furrow was 0.0134 m^2. The results of cumulative infiltration water amounts were calculated every 5 m, as shown in Tables 2, 3 and 4. The final distributions of infiltration amounts are described in Fig. 4, 5 and 6.

The water application efficiency values were 54.2, 60.5, and 59.2 %. The maximum water application efficiency was 60.5 % with an irrigation discharge of 0.002 m^3/s for a furrow (Fig. 5). This shows that the conventional irrigation water amount in one furrow with a length of 40 m is equal to 0.934 m^3. According to our estimates of the optimum irrigation water discharge in one furrow of a standard size, it is equal to 0.883 m^3. The difference in the total amount of irrigation water between the conven-

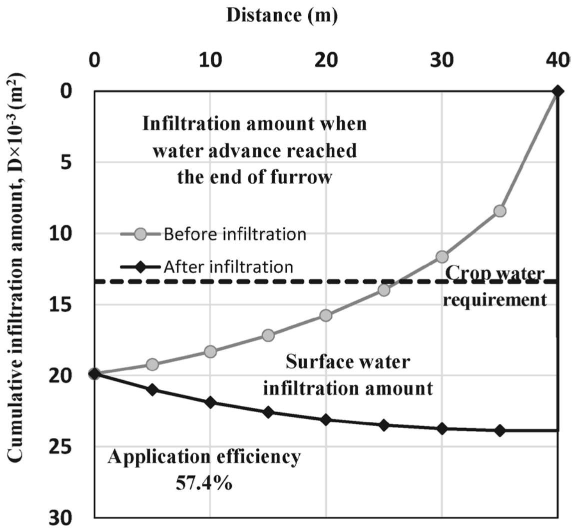

Fig. 3 Actual infiltration amounts, $q = 0.00148\ m^3/sec$

Table 2 Calculation results of cumulative infiltration amounts, $q = 0.0011\ m^3/s$

advance distance (m)	infiltration time (s)	cumulative infiltration amount (m^2)
0	899	0.0241541
5	850	0.023485
10	780	0.0224947
15	695	0.0212305
20	595	0.01964
25	478	0.0175985
30	343	0.0149013
25	185	0.0109351
40	0	0

Table 3 Calculation results of cumulative infiltration amounts, $q = 0.002\ m^3/s$

advance distance (m)	infiltration time (s)	cumulative infiltration amount (m^2)
0	442	0.016921
5	409	0.016276
10	369	0.015457
15	321	0.014414
20	268	0.013168
25	209	0.011625
30	145	0.009678
25	75	0.006955
40	0	0

Table 4 Calculation results of cumulative infiltration amounts, $q = 0.003\ m^3/s$

advance distance (m)	infiltration time (s)	cumulative infiltration amount (m^2)
0	306	0.0141
5	280	0.0135
10	249	0.0127
15	215	0.0118
20	177	0.0107
25	137	0.0094
30	94	0.0078
25	48	0.0056
40	0	0

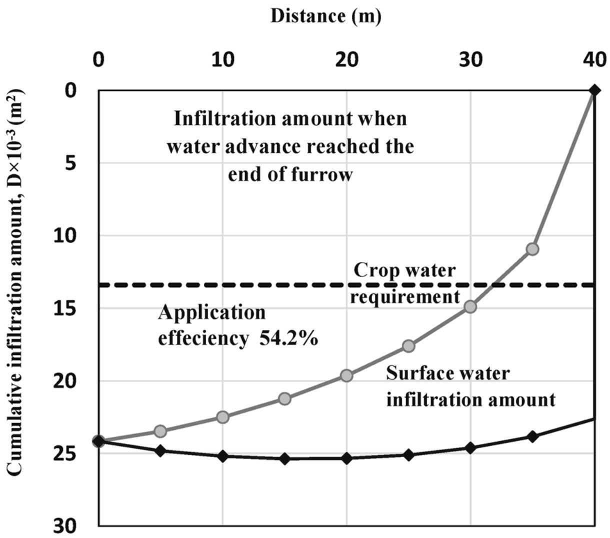

Fig. 4 Simulation infiltration amounts, $q = 0.0011\ m^3/sec$

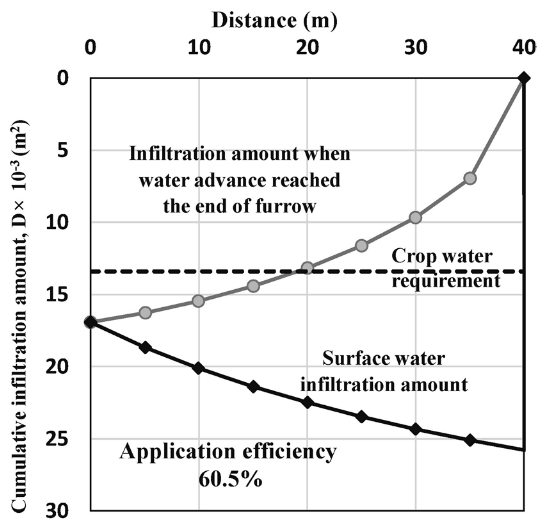

Fig. 5 Simulation infiltration amounts, $q = 0.002\ m^3/sec$

tional irrigation method as managed by a farmer and our simulated optimum irrigation water is equal to $0.051\ m^3$. This value is a small amount of water for one furrow. However, it is intended to calculate the amount of irrigation water needed for one hectare of land with less than 40-m in length under furrows for irrigation. If we finally consider irrigating tomato fields in one hectare of land

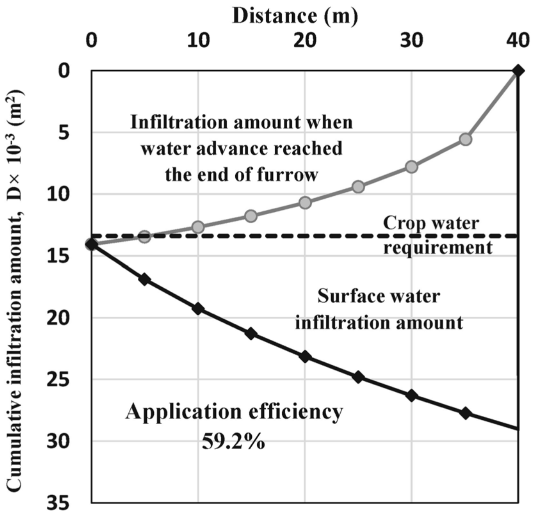

Fig. 6 Simulation infiltration amounts, q = 0.003 m^3/sec

that has 100 furrow lines 40 meters long and under water discharge of 0.002 m^3/s, 5.1 m^3 of water per hectare could be saved as compared to existing irrigation conditions in each irrigation schedule.

Conclusions

Water management under arid and semi-arid zones in irrigated agricultural land includes multiple faces; one of them is a system of modified water discharge in furrow irrigation in Afghanistan to reduce runoff losses and deep percolation. The use of measured water flows has proved vital for application efficiency. This study found that the actual water discharge of 0.001489 m^3/sec used by local farmers had an application efficiency of 57.4 % after irrigation and infiltration of the furrows. Estimates of 0.0011 m^3/sec, 0.002 m^3/sec and 0.003 m^3/sec water discharge application efficiency improved by different percentages. Especially, irrigation discharge at 0.002 m^3/sec had the highest application efficiency value. This was 3.1 % higher than for a conventional irrigation discharge estimated for one hectare of land with 100 line irrigation furrows 40 meters long. It was also possible to save 5.1 m^3/ha of water in one scheduled irrigation. This water advance approach can be applied to estimating optimum irrigation discharge for furrow irrigation. It is important to conduct further research on other crops to identify the best practice for reducing the amount of water needed for furrow irrigation.

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アフガニスタンにおける畦間灌漑への最適灌漑水量の推定

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要約：畦間灌漑とは，畑地で畦と畦の間に水を流して作物に水を補給する地表灌漑法の一つである。この方法は，スプリンクラーなどのような散水灌漑法とは異なり，加圧ポンプやパイプラインなどの施設が不要なため水があれば容易に導入ができる。そのため，世界の灌漑農地の 75％ 以上に導入されている。一方，この灌漑法は，作物の根の分布するところにムラなく水を給水することがしばしば困難で，とくに作物の根群域よりさらに深部へ灌漑水が浸透し，多量の浸透ロスが発生することが最大の短所である。この浸透ロスを抑制するために，多くの研究が行われてきているが，圃場レベルでの地表灌漑における浸潤量分布を改善する技術はまだ十分確立されていないのが現状である。そこで，本研究では，灌漑水の無駄のない均一な浸潤分布になる給水量の決定法を提案し，さらにその手法をアフガニスタンのトマト畑に適用することを目的とした。まず，畦間に供給された水が地中にしみ込みながら地表流下する水収支式の積分方程式の解析解を用いて，現場で実施された水足試験から土壌の浸潤特性を表すインテーク定数を決定し，異なる給水量における水足の到達時間を計算した。次に，上流側の水口から畦間の末端部での浸潤分布がほぼ均一になる給水量の推定が可能であることを明らかにした。最後に，アフガニスタンのトマト畑で実施されている畦間灌漑において，現場水足試験で得られたデータから灌漑水の浸潤量分布がほぼ均一な適正給水量を適用効率を指標に決定した。その結果，現地で行われている灌漑法に比較して適用効率を約 3％ 向上させることができること，さらに 1 ha のトマト畑全体で 1 回の灌漑で 5.1 m^3 の節水が可能であることを明らかにした。

キーワード：畦間灌漑，水収支式，水足，最適灌漑水量，アフガニスタン

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